Breaking the Speed of Light Barrier

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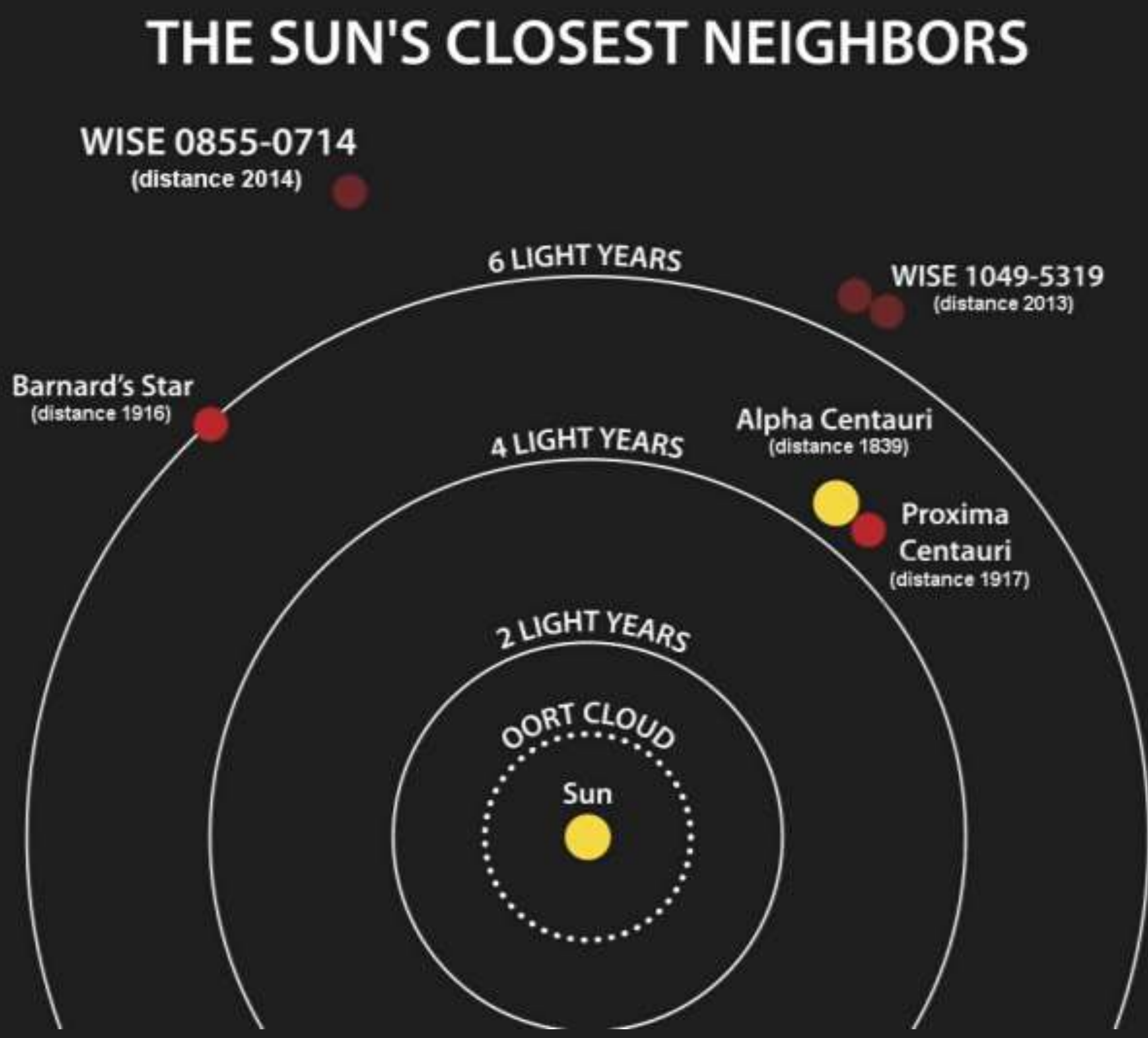
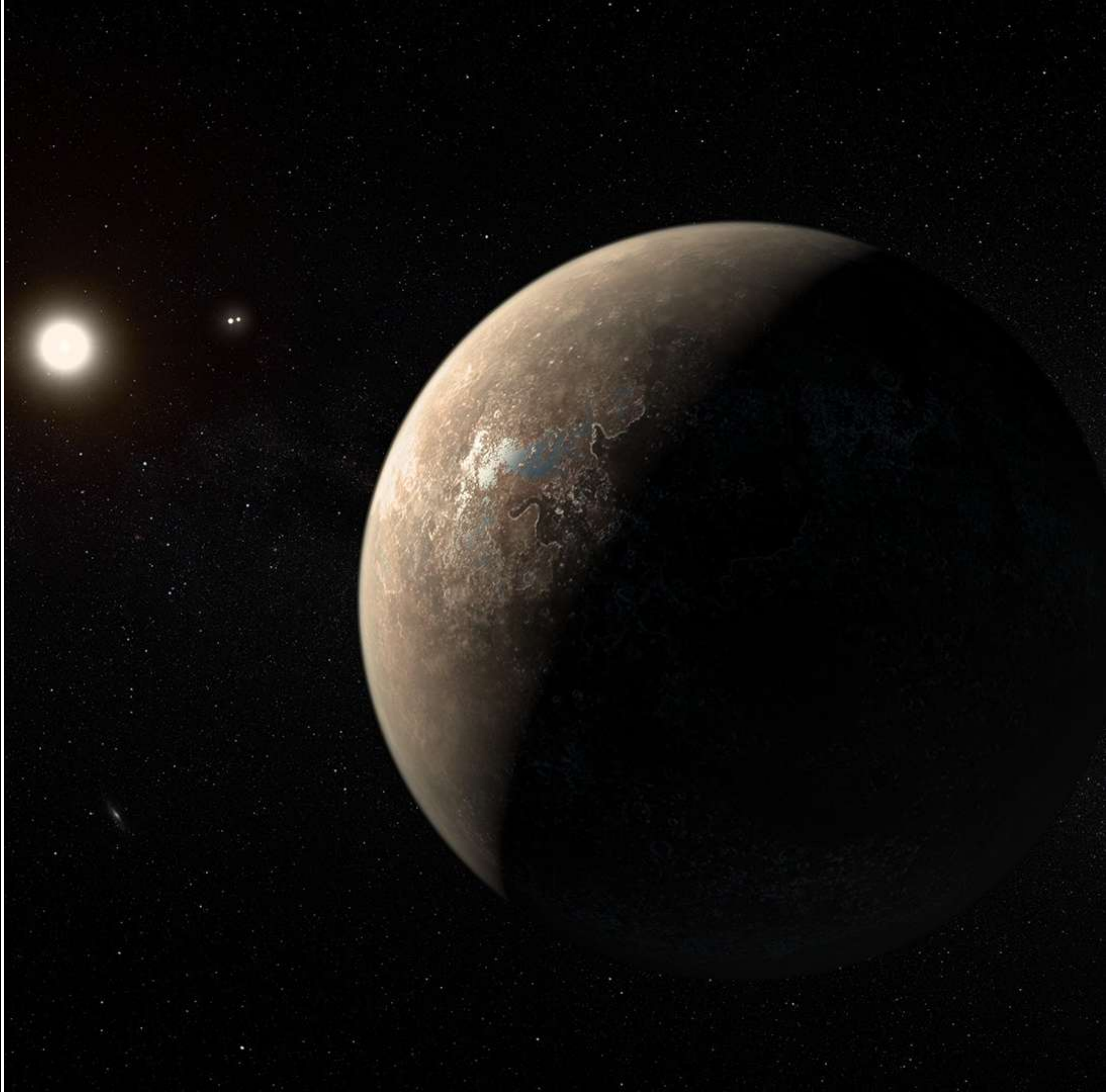
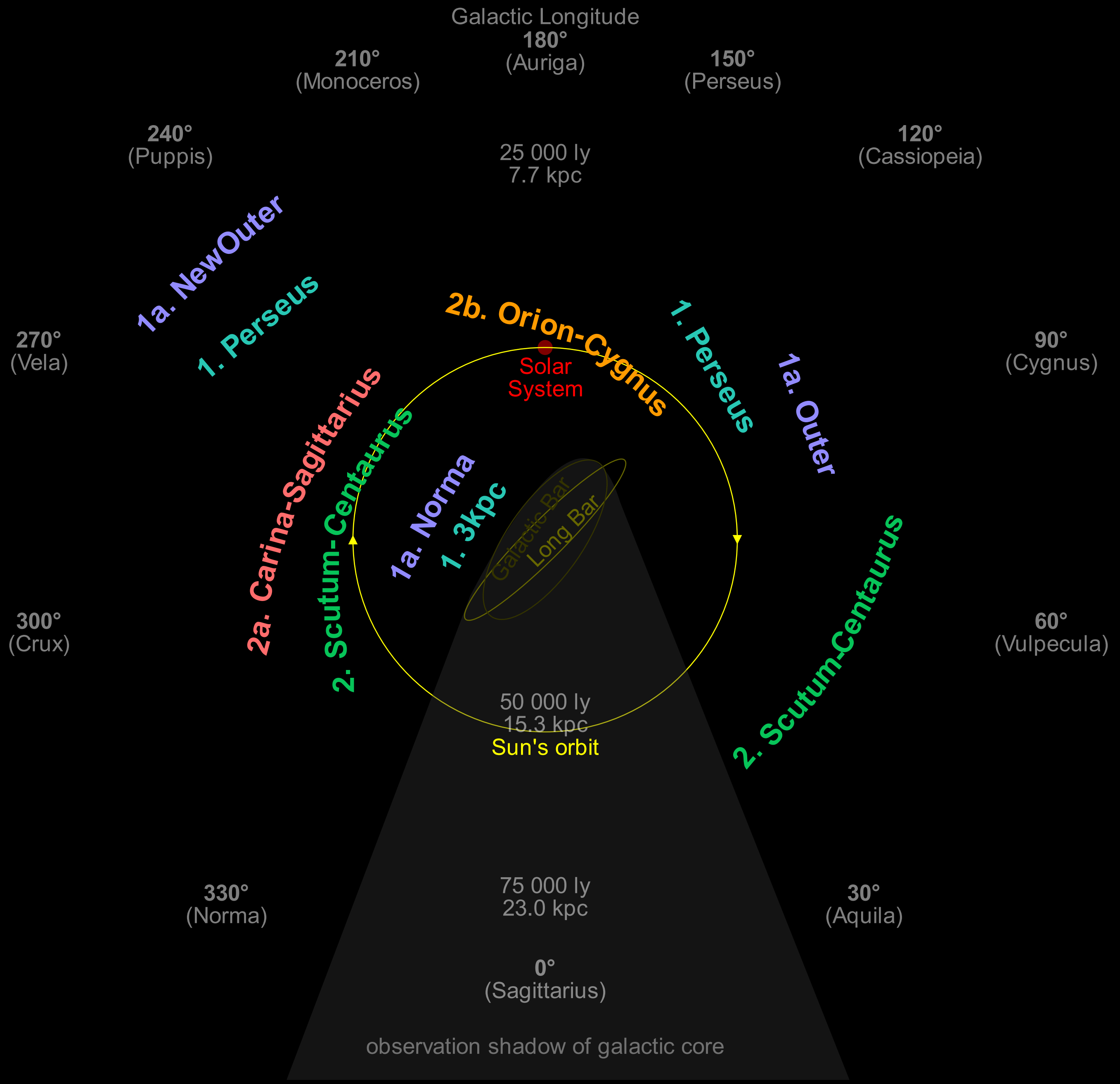
- Where can we travel in space?
- Interstellar travel: between stars.
- Closest star system: Alpha Centauri, 4.4 light-years away.
- Closest star: Proxima Centauri (Alpha Centauri C).



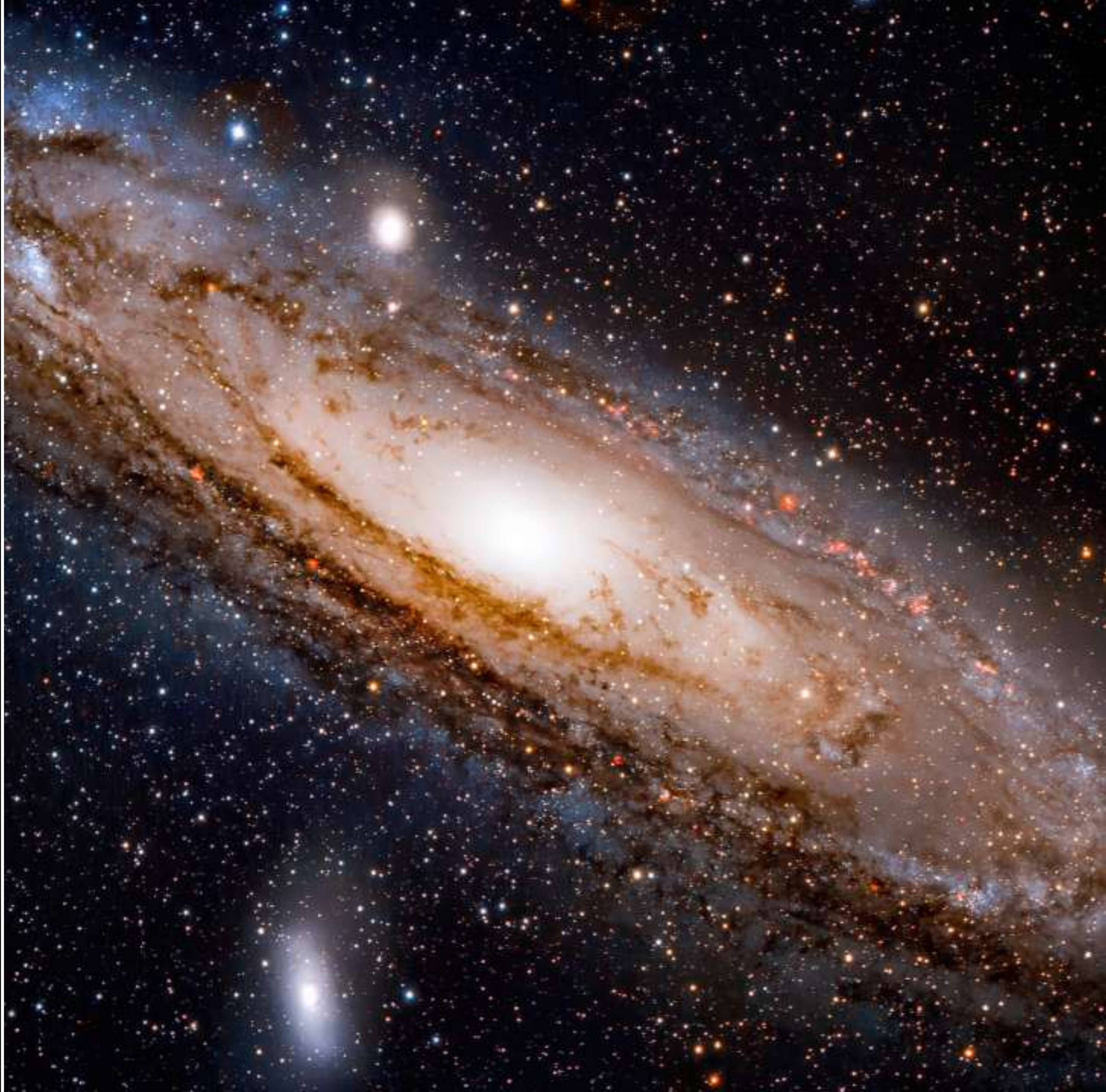
- Closet exoplanet: Proxima Centauri b.
- Potentially habitable.



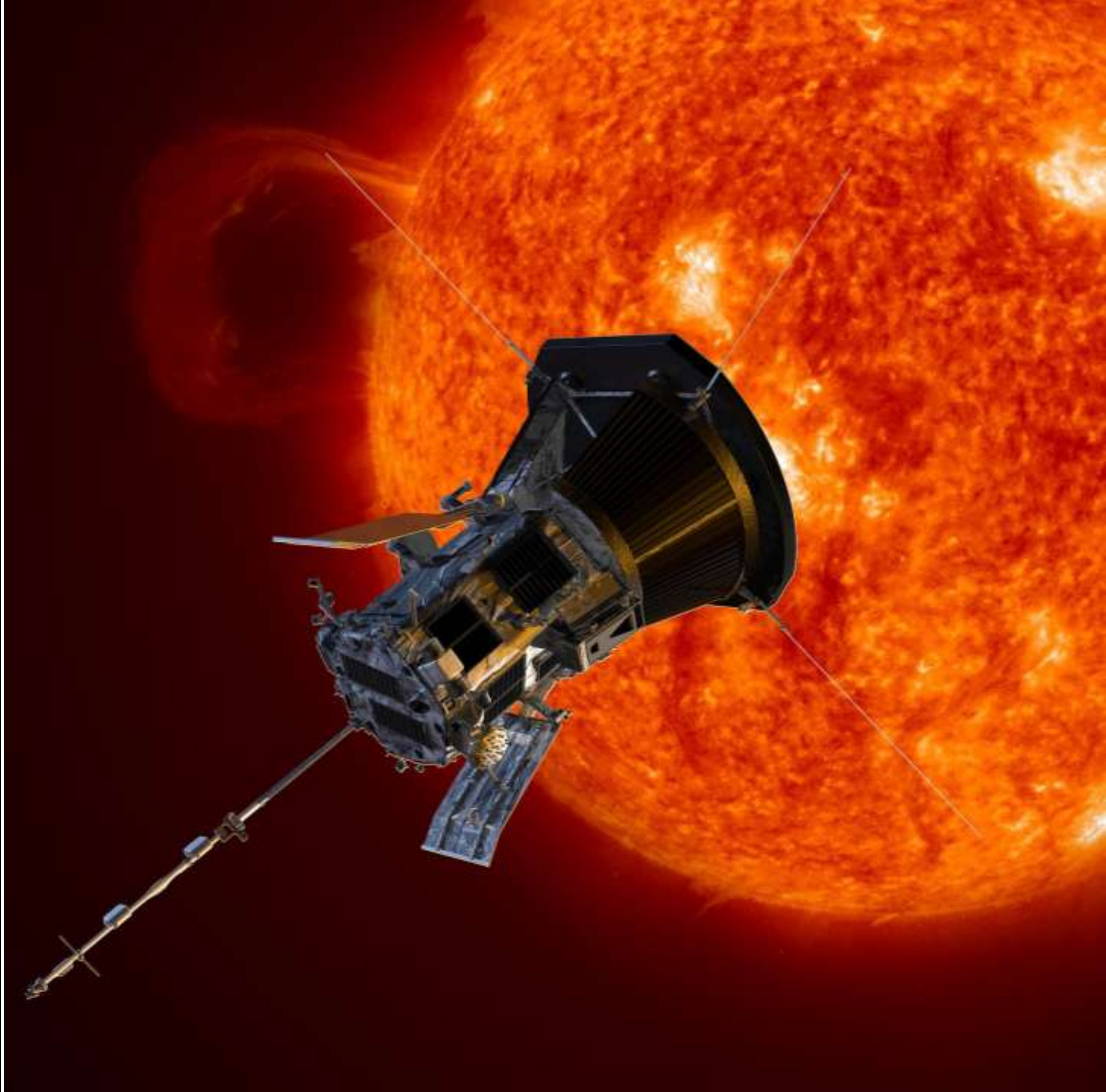
- Diameter of Milky Way galaxy: 87,000 light-years.
- The Sun is 26,000 light-years from the galactic center.



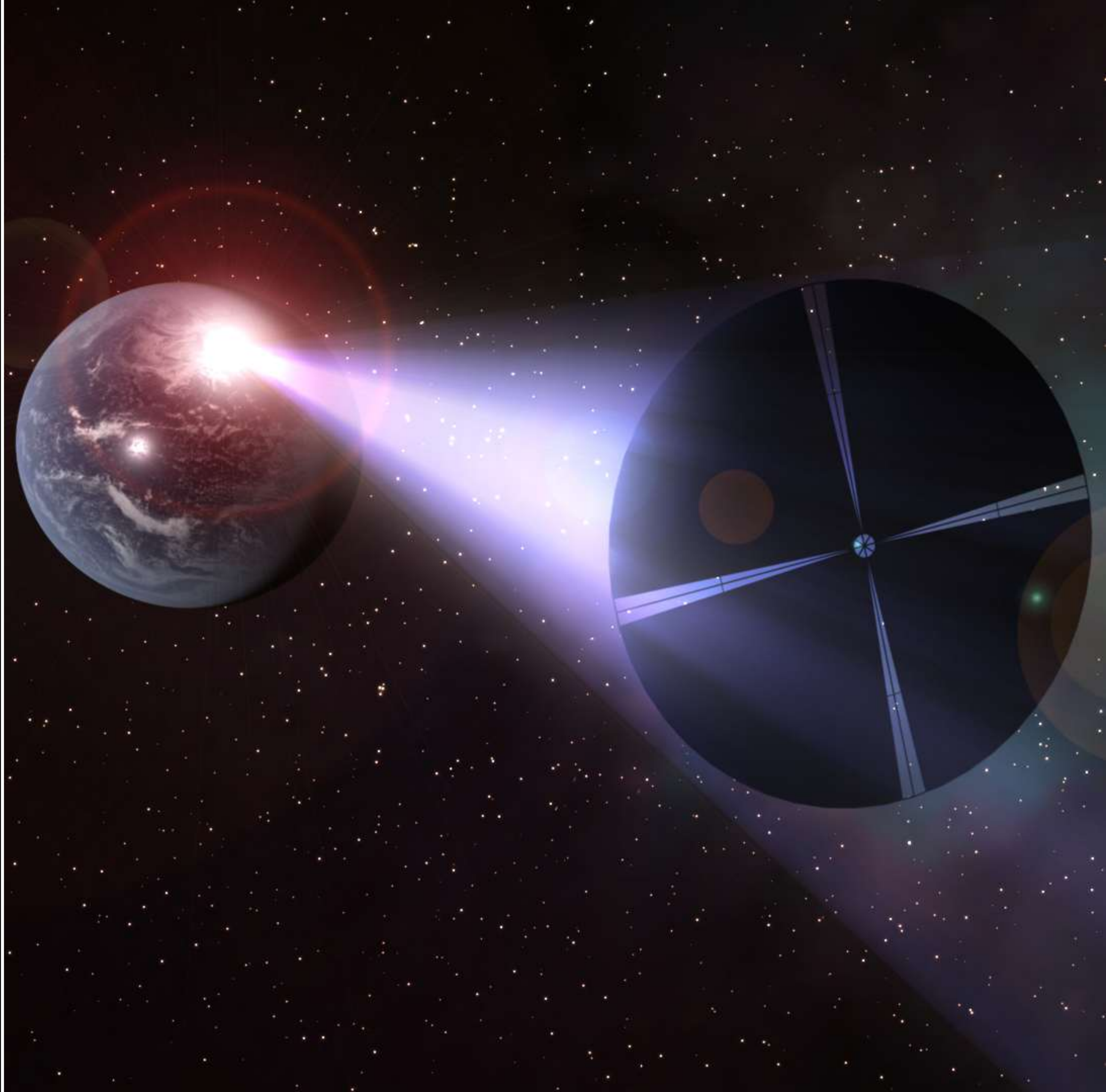
- Intergalactic travel: between galaxies.
- Closet large galaxy: Andromeda.
- Distance: 2.5 million light-years!



- How long will a journey take?
- Fastest human-made spacecraft: Parker Solar Probe.
- Its peak speed (Dec 2024):
  - 690,000 km/h.
  - 190 km/s.
  - 0.064% of speed of light.
- At this speed:
  - 6,900 years to Alpha Centauri.
  - 4 billion years to Andromeda.



- Prospective propulsion methods:
  - Nuclear pulse
  - Light sail
- Could reach 10% of speed of light ($.1c$).
- 44 years to Alpha Centauri.
- NASA planned mission: launch in 2069, get there by 2113.
- 25 million years to Andromeda.



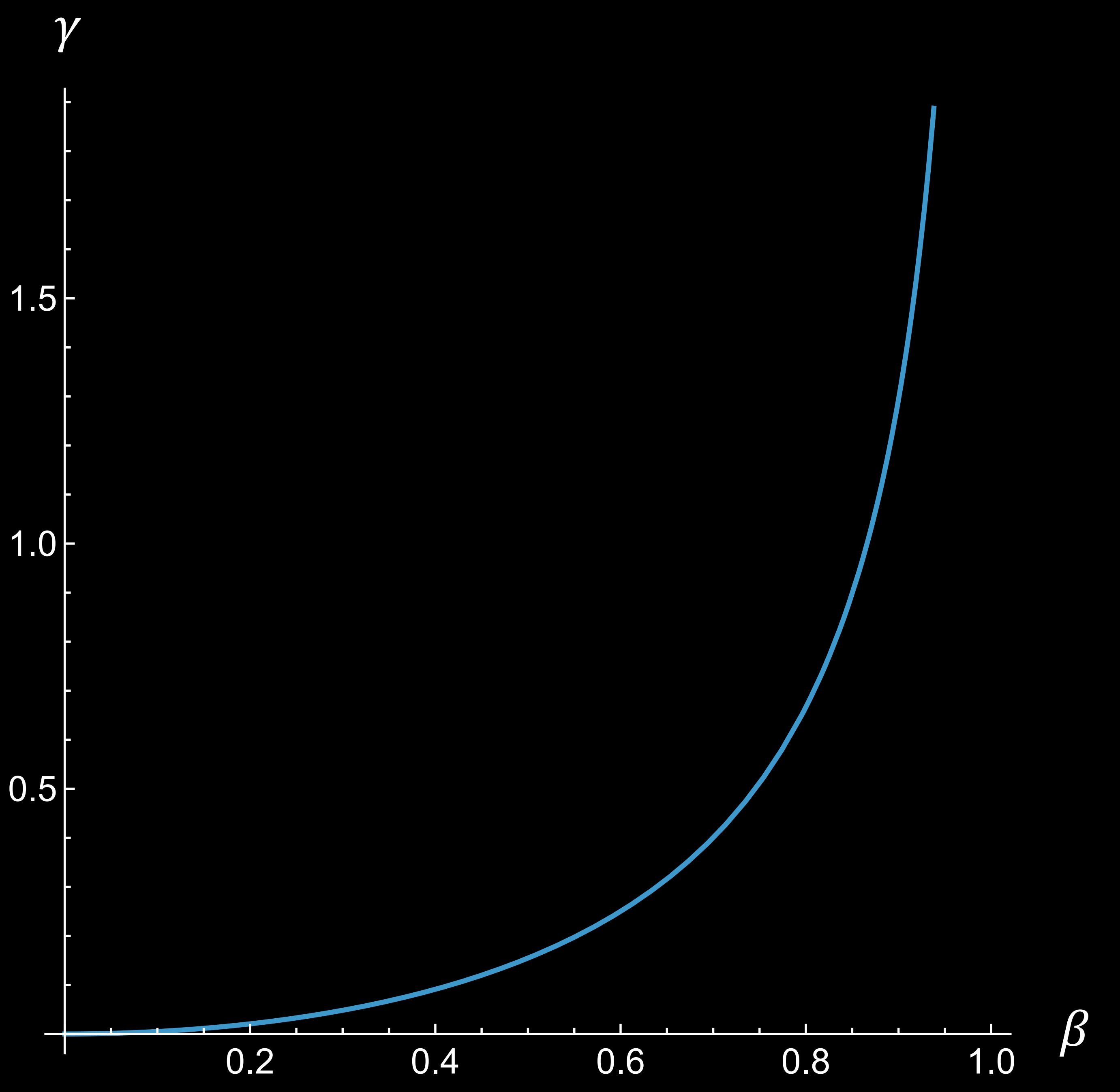
- What is the fastest possible speed?
- As a massive object approaches the speed of light, accelerating requires more and more energy.

$$\beta \equiv \frac{v}{c}$$

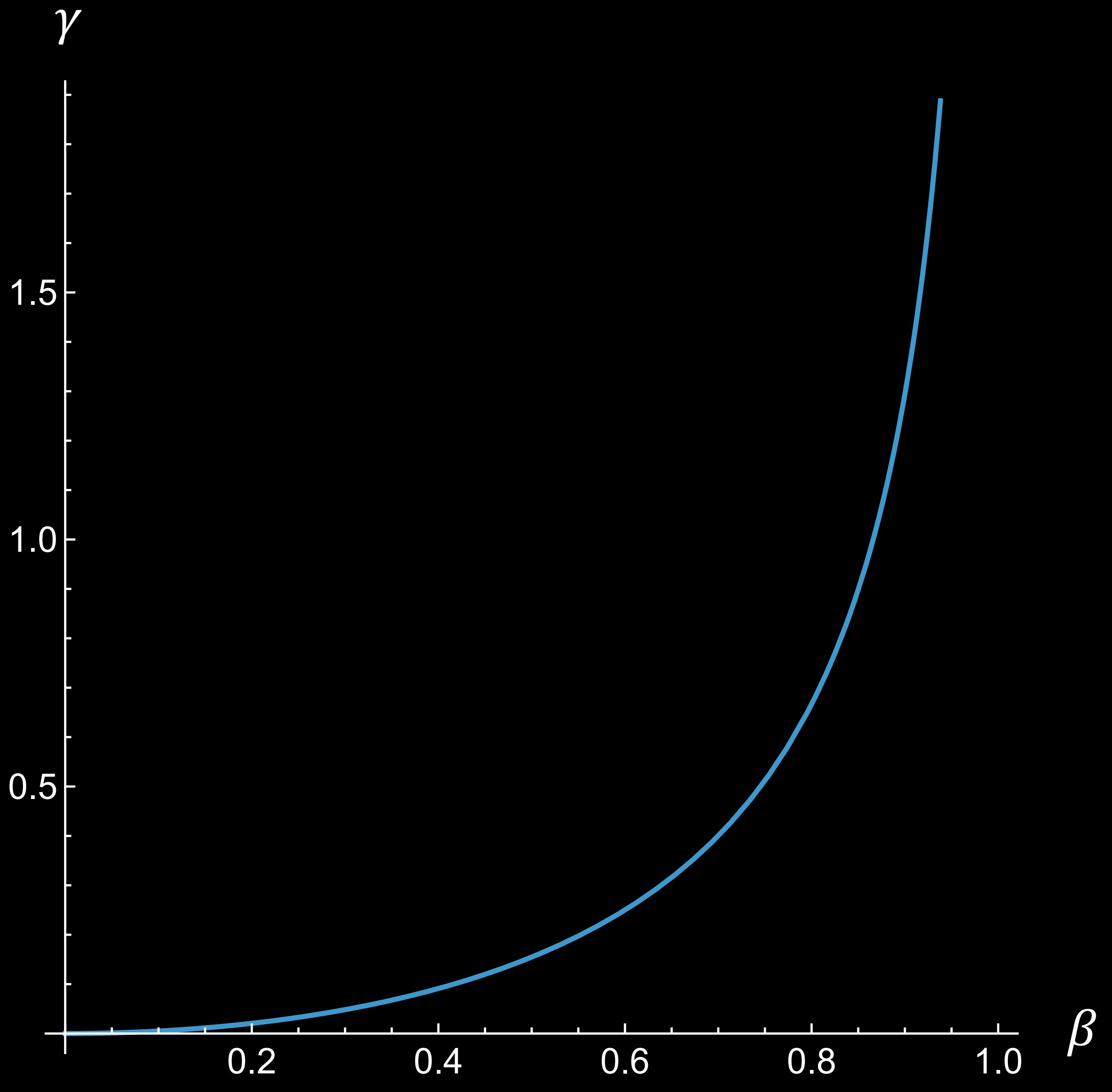
$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}}$$

$$E = \gamma mc^2$$

$$K = (\gamma - 1)mc^2$$



- Distant future propulsion methods could get arbitrarily close to c, given enough energy.
- How much energy?



- Accelerate $m \approx 1$ ton to $v \approx .99c$?
- $E \approx 10^{21}$ J (total world energy consumption in a year).
- Double for deceleration at destination.
- Alpha Centauri in 4.4 years.
- Andromeda in 2.5 million years.

- Relativistic time dilation makes the trip subjectively shorter for the passengers on the ship (but NOT on Earth).
- At $.99c$, dilation factor is $\gamma \approx 7$.
- Trip to Alpha Centauri will take 7.5 months.
- To Andromeda 360,000 years.

- At $.9999999999999c$, dilation factor is 2,500,000.
- Trip to Alpha Centauri will take just 1 minute!
- Trip to Andromeda will take just 1 year.
- But:
  - This requires 1 million times more energy than $.99c$.
  - Back on Earth time flows normally.

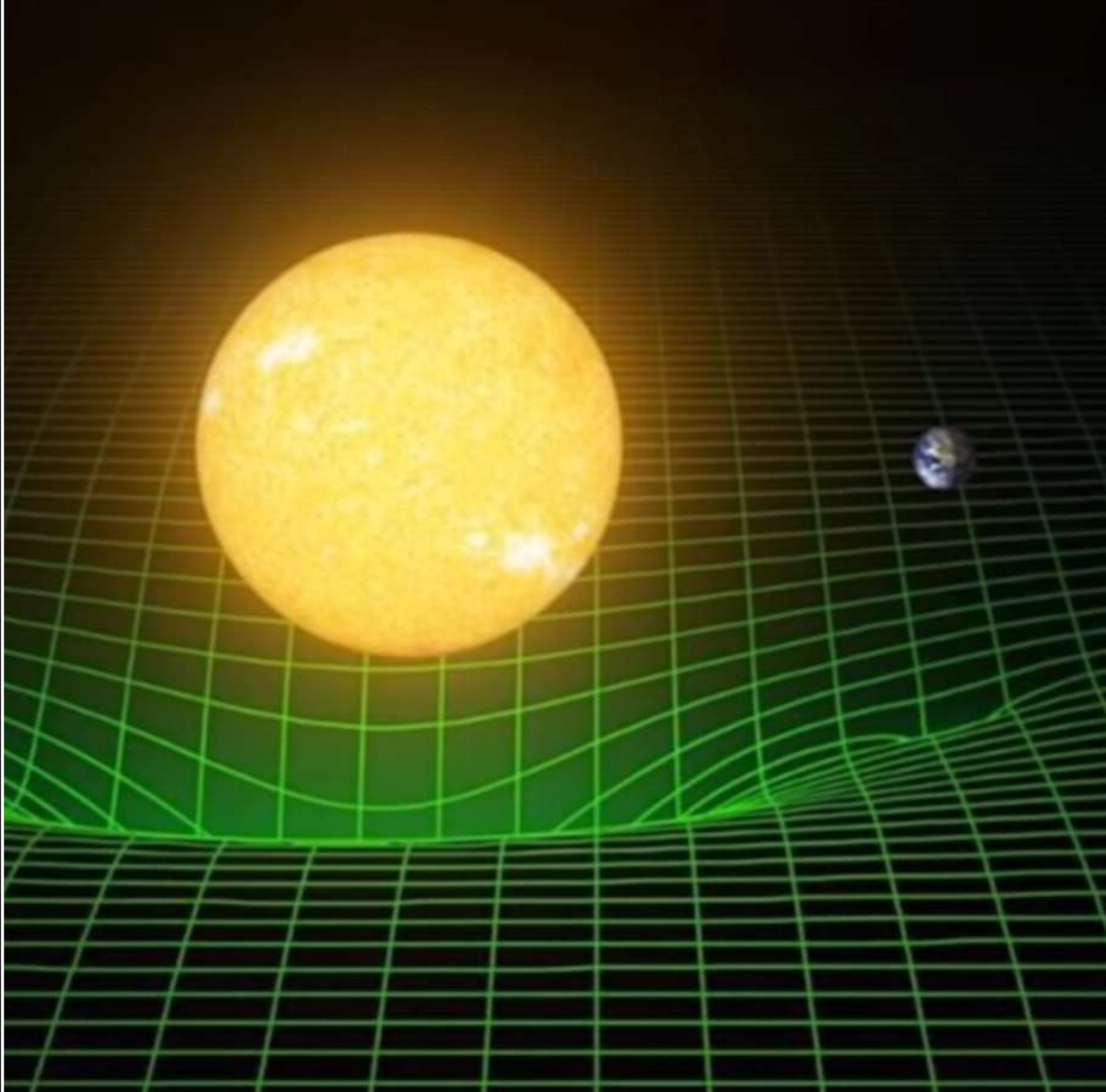
- What can we do with limited energy and very long journeys?
- Generation ship: Multiple generations live and die on ship.

- Sleeper ship: Crew in suspended animation.

- Extended lifetimes or immortality.

- Send AIs instead (or mind upload).
- Conclusion: Interstellar travel is extremely hard, intergalactic travel nearly impossible!

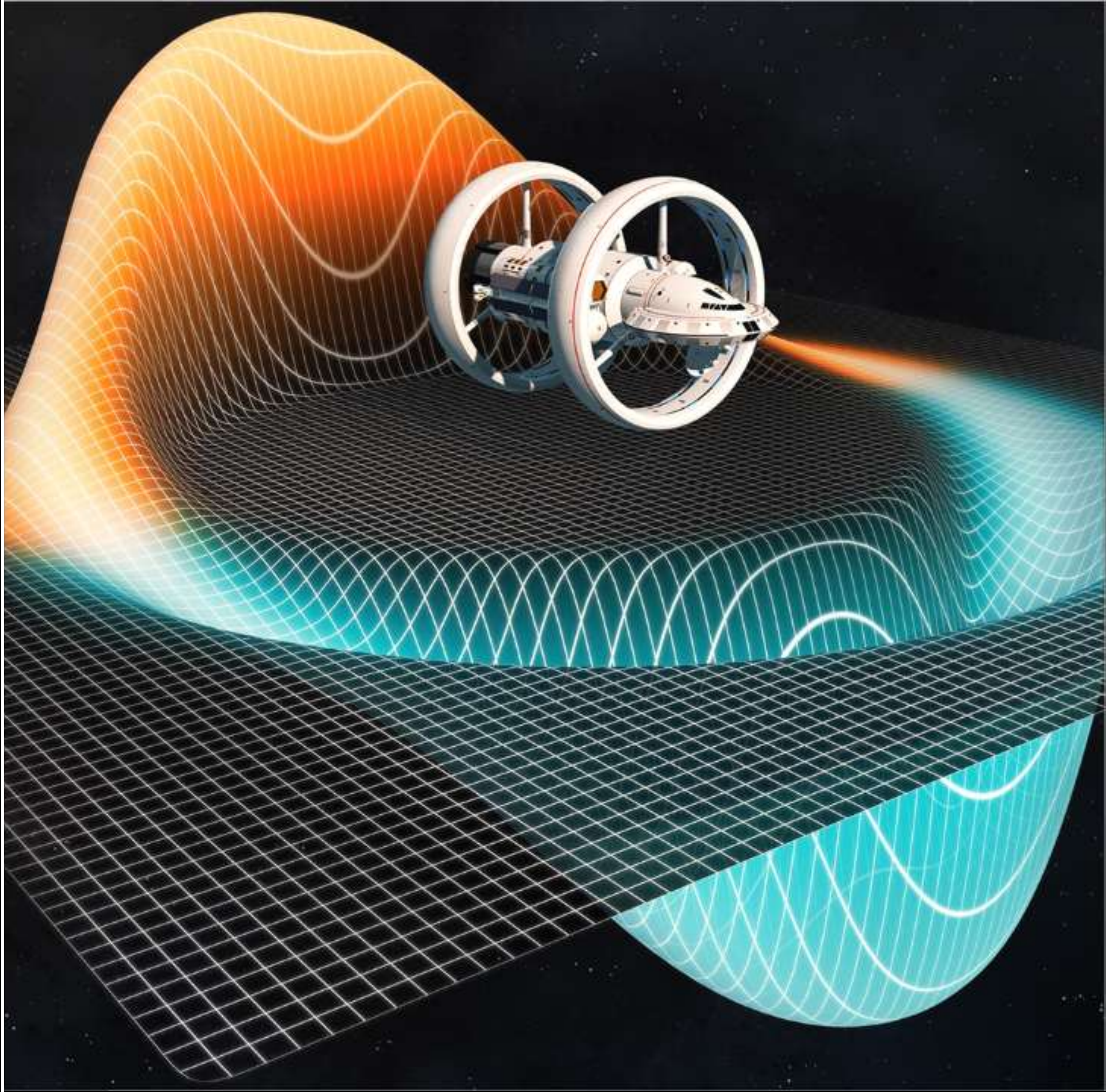
- Can we travel faster than light (FTL)?
- In general relativity, spacetime is curved.
- This seems to allow “loopholes” for FTL travel.



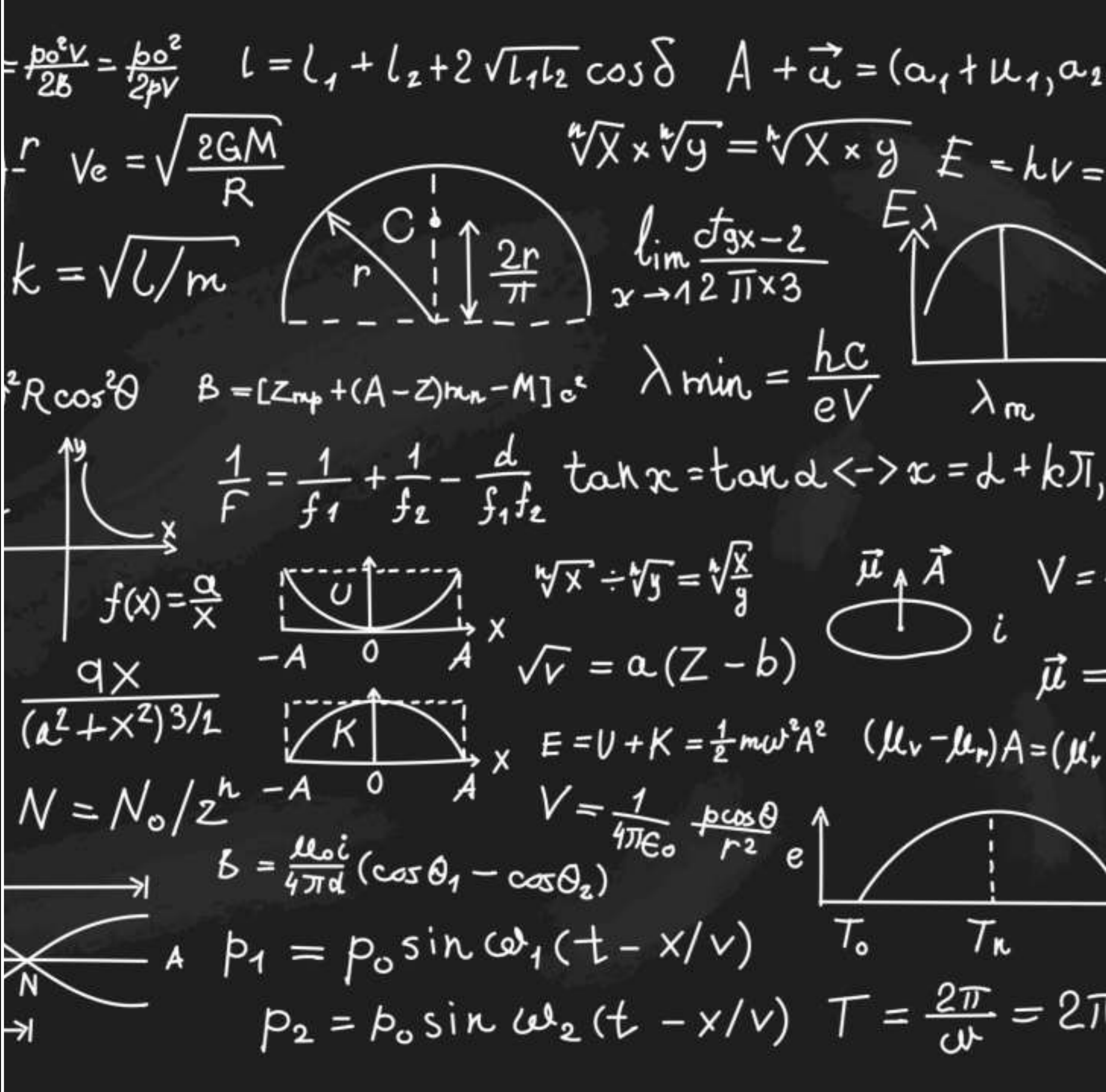
- First “loophole”: wormholes, “shortcuts” in spacetime.
- Imagine a wormhole with one end at Earth and the other at Proxima Centauri b.
- We can travel the distance through the wormhole instantly.
- Travel through the wormhole is actually slower than light, but effectively FTL.

A wormhole between the Brock University exterior and the Physics Department. Credit: Alessandro Pisana.

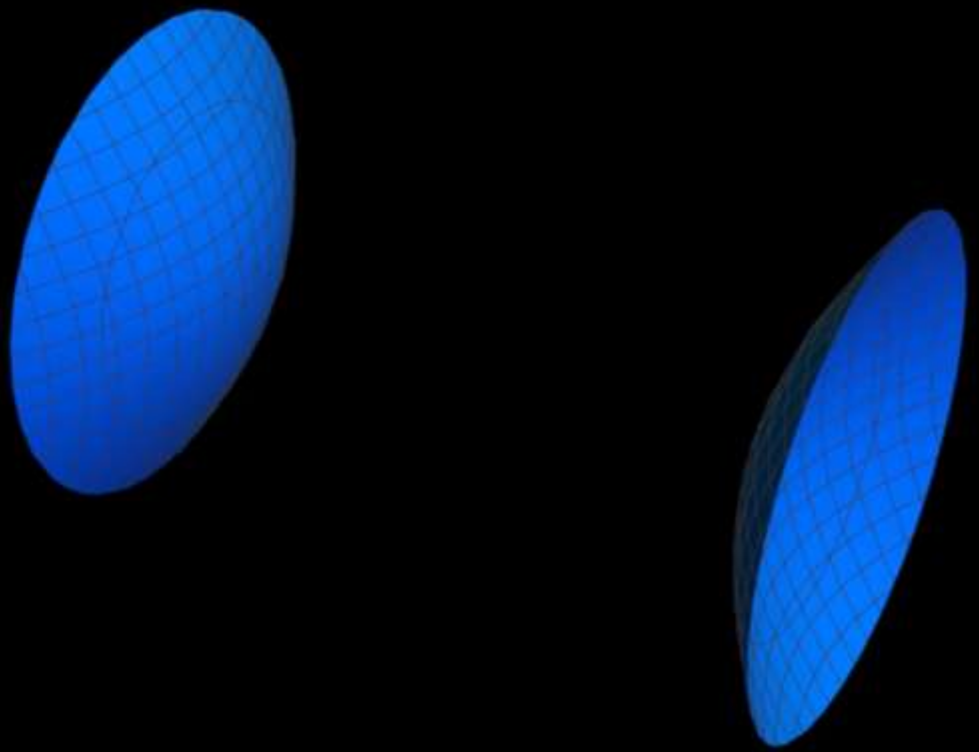
- Second “loophole”: warp drives.
- Relativity: no FTL within space.
- But space itself can move at any speed.
- The warp bubble moves FTL on its own due to its curvature.
- Spaceship is at rest inside the bubble.



- Are they realistic?
- Both “loopholes” can be described mathematically.
- That doesn’t mean they can really exist.
- One issue: both require exotic matter with negative energy.
- It can exist only in very small quantities for a short time.



- Another issue: we don’t know how to construct them.
- All existing theoretical research just assumes they already exist.
- For wormholes, we need to somehow “make a hole” in spacetime.
- For warp drives, we need to already travel FTL to create the FTL bubble.



Creation of a wormhole. Credit: Alessandro Pisana.

- FTL travel can also lead to time travel.
- Wormholes can connect two spacetime points at different times.
- Warp drives can also be used to travel back in time.
- A bug or a feature?

- Time travel could lead to paradoxes.
- Examples:
  - Consistency paradox: something prevents itself (grandfather paradox).
  - Bootstrap paradox: something creates itself.
- A paradox isn't an event that can happen, it's a theoretical inconsistency.

- Proposed resolutions:
  - Hawking Chronology Protection Conjecture: Time travel is impossible.
  - Novikov Self-Consistency Conjecture: Paradoxes are impossible.
  - Parallel timelines : Changes create new independent timeline.

My research

Time Travel Paradoxes and Multiple Histories

With Jacob Hauser

Phys. Rev. D 102, 064062 (2020)

Main results:

- Model with **inevitable** paradoxes.
- Cannot be solved using Novikov.
- Can be solved using parallel timelines.
- Either infinite or cyclic histories.

Time travel paradoxes and multiple histories

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If time travel is possible, it seems to inevitably lead to paradoxes. These include consistency paradoxes, such as the famous grandfather paradox, and bootstrap paradoxes, where something is created out of nothing. One proposed class of resolutions to these paradoxes allows for multiple histories (or timelines) such that any changes to the past occur in a new history, independent of the one where the time traveler originated. We introduce a simple mathematical model for a spacetime with a time machine and suggest two possible multiple-histories models, making use of branching spacetimes and covering spaces, respectively. We use these models to construct novel and concrete examples of multiple-histories resolutions to time travel paradoxes, and we explore questions such as whether one can ever come back to a previously visited history and whether a finite or infinite number of histories is required. Interestingly, we find that the histories may be finite and cyclic under certain assumptions, in a way which extends the Novikov self-consistency conjecture to multiple histories and exhibits hybrid behavior combining the two. Investigating these cyclic histories, we rigorously determine how many histories are needed to fully resolve time travel paradoxes for particular laws of physics. Finally, we discuss how observers may experimentally distinguish between multiple histories and the Hawking and Novikov conjectures.

DOI: 10.1103/PhysRevD.102.064062

I. INTRODUCTION

The theory of general relativity, which describes the curvature of spacetime and how it interacts with matter, has been verified to very high precision over the last 100 years. As far as we can tell, general relativity seems to be the correct theory of gravity, at least in the regimes we can test. However, within this theory there exist certain spacetime geometries which feature *closed timelike curves* (CTCs) or, more generally, *closed causal*[1] *curves* (CCCs), thus allowing the violation of causality [1–4]. The fact that these geometries are valid solutions to Einstein's equations of general relativity indicates crucial gaps in our understanding of gravity, spacetime, and causality.

Wormhole spacetimes and cosmological models admitting CTCs were first explored in the decades following the discovery of general relativity [5–7]. Although these spacetimes were clearly unphysical—the wormholes were nontraversable and the cosmologies unrealistic—they were followed, several decades later, by *traversable wormholes*, *warp drives*, and other spacetimes potentially supporting time travel [8–13].

These exotic geometries which allow violations of causality almost always violate the *energy conditions* [14], a set of assumptions imposed by hand and thought to ensure that matter sources in general relativity are "physically reasonable." However, it is unclear whether or not these conditions themselves are justified, as many realistic physical models—notably, quantum fields—also violate some or all of the energy conditions.

In this paper, we consider two types of causality violations: *consistency paradoxes* and *bootstrap paradoxes*. A familiar example of a consistency paradox is the *grandfather paradox*, where a time traveler prevents their own birth by going to the past and killing their grandfather before he met their grandmother. This then means that the time traveler, having never been born, could not have gone back in time to prevent their own birth in the first place.

More precisely, we define a consistency paradox as the absence of a consistent evolution for appropriate initial conditions under appropriate laws of physics. Following Krasnikov [15], "appropriate initial conditions" are those defined on a spacelike hypersurface in a *causal region* of spacetime—that is, a region containing no CTCs—and "appropriate laws of physics" are those which respect locality and which allow consistent evolutions for all initial conditions in entirely causal spacetimes.

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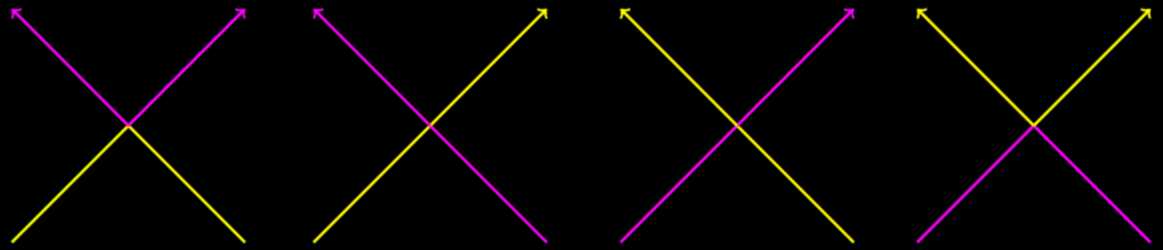
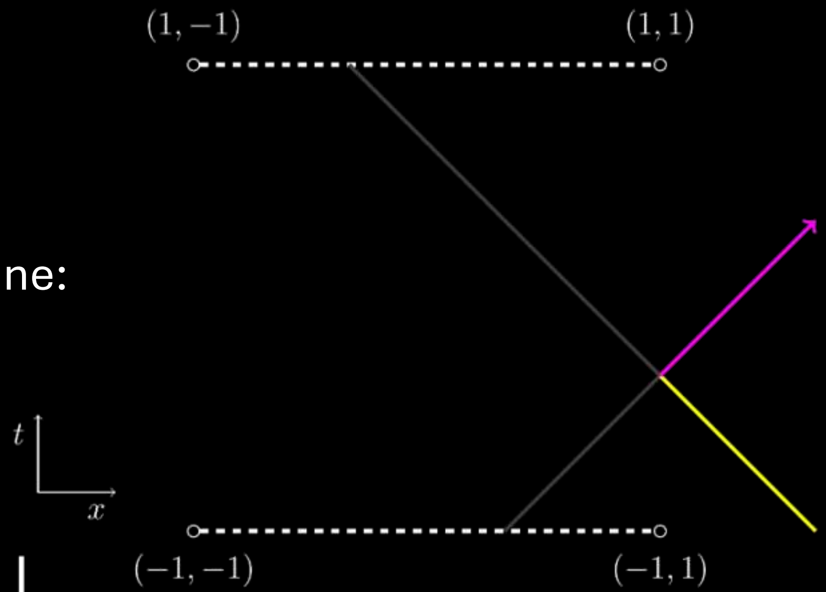
[1]Here by "causal" we mean either timelike or null.

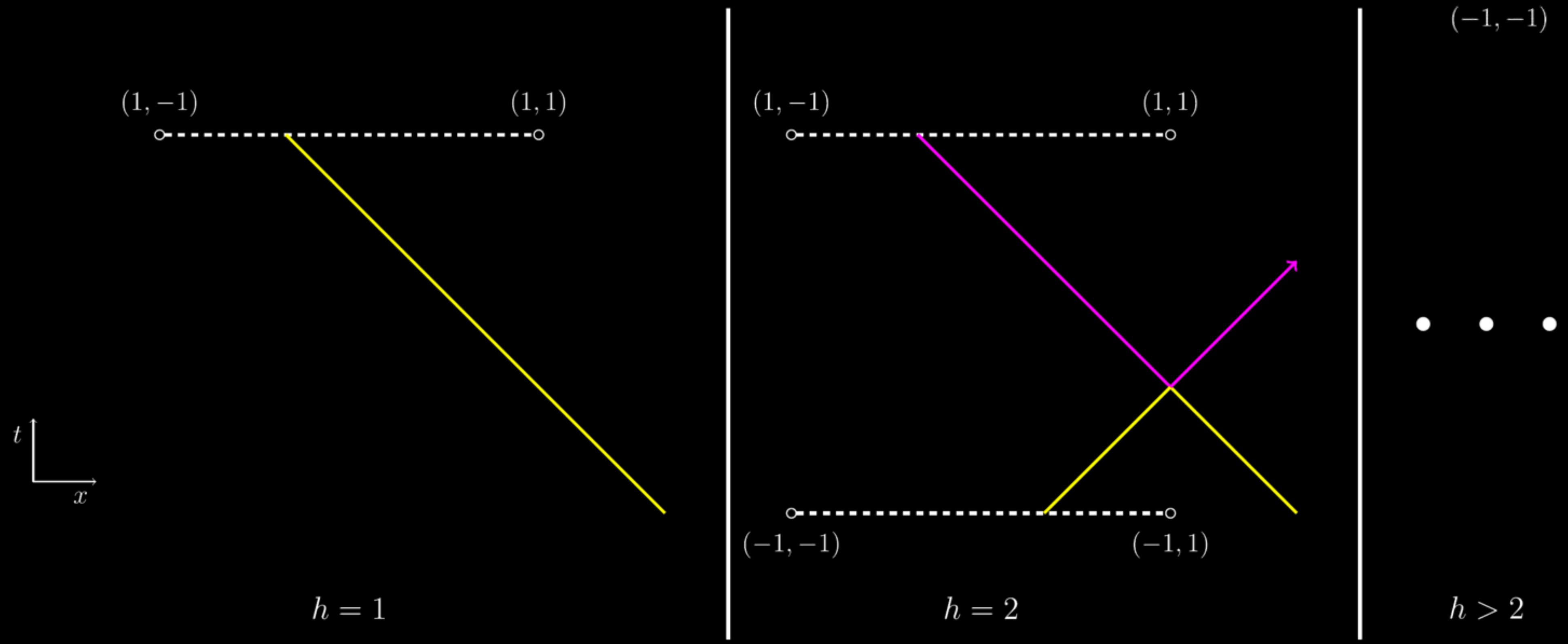
Allowed interactions:



One timeline:



Many timelines:



Wormhole Time Machines and Multiple Histories

With Jared Wogan

Gen. Relativ. Gravit. 55, 44 (2023)

Main results:

- Strengthened previous results using a realistic model + simulation.
- Proved that parallel timelines are mandatory if time travel is possible.

General Relativity and Gravitation (2023) 55:44
https://doi.org/10.1007/s10714-023-03094-8

RESEARCH ARTICLE

Wormhole Time Machines and Multiple Histories

Barak Shoshany[1] · Jared Wogan[1]

Received: 22 August 2022 / Accepted: 10 February 2023

Abstract

In a previous paper, we showed that a class of time travel paradoxes which cannot be resolved using Novikov's self-consistency conjecture can be resolved by assuming the existence of multiple histories or parallel timelines. However, our proof was obtained using a simplistic toy model, which was formulated using contrived laws of physics. In the present paper we define and analyze a new model of time travel paradoxes, which is more compatible with known physics. This model consists of a traversable Morris-Thorne wormhole time machine in 3+1 spacetime dimensions. We define the spacetime topology and geometry of the model, calculate the geodesics of objects passing through the time machine, and prove that this model inevitably leads to paradoxes which cannot be resolved using Novikov's conjecture, but can be resolved using multiple histories. An open-source simulation of our new model using Mathematica is available for download on GitHub. We also provide additional arguments against the Novikov self-consistency conjecture by considering two new paradoxes, the switch paradox and the password paradox, for which assuming self-consistency inevitably leads to counter-intuitive consequences. Our new results provide more substantial support to our claim that if time travel is possible, then multiple histories or parallel timelines must also be possible.

Contents

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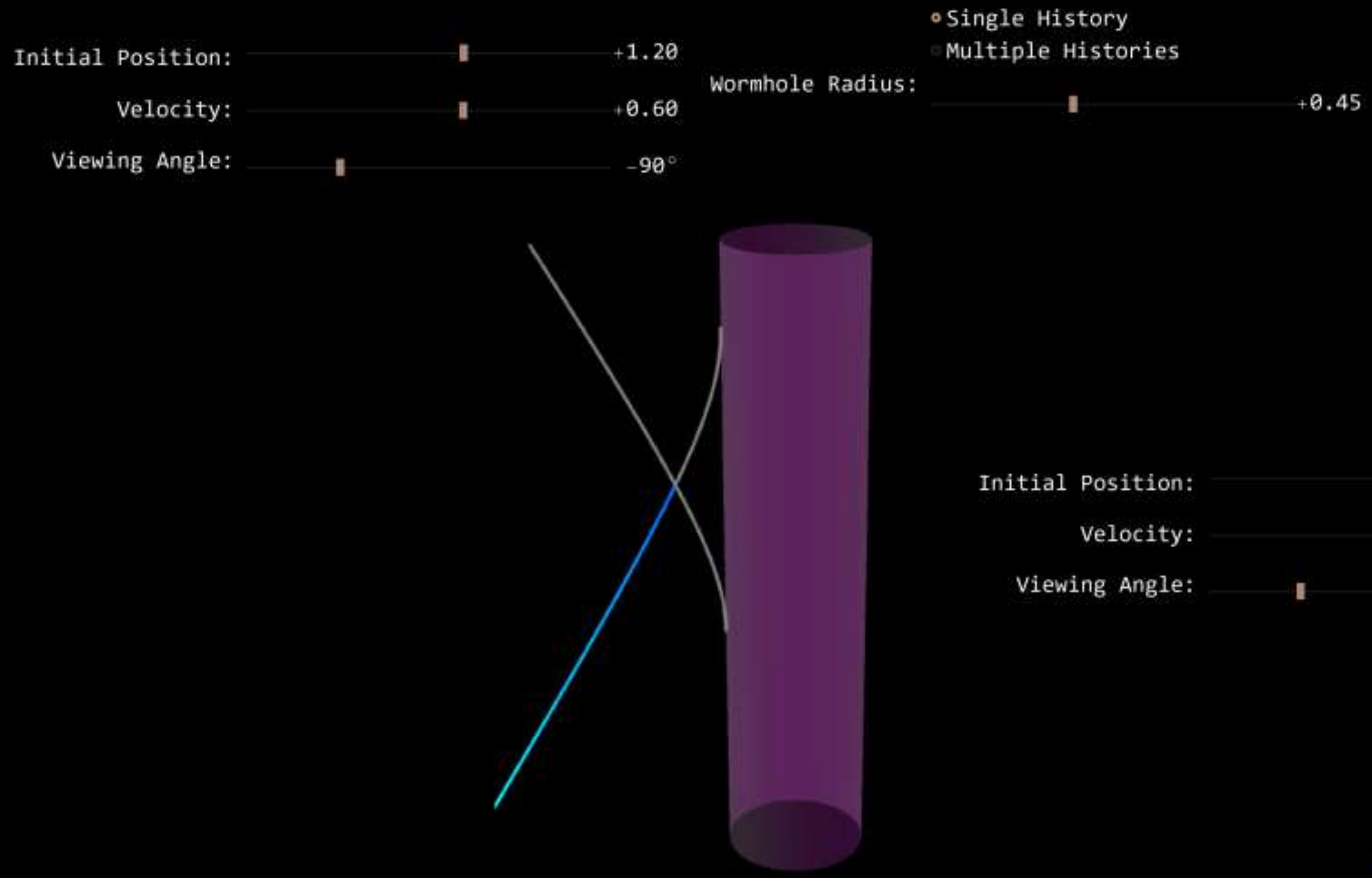
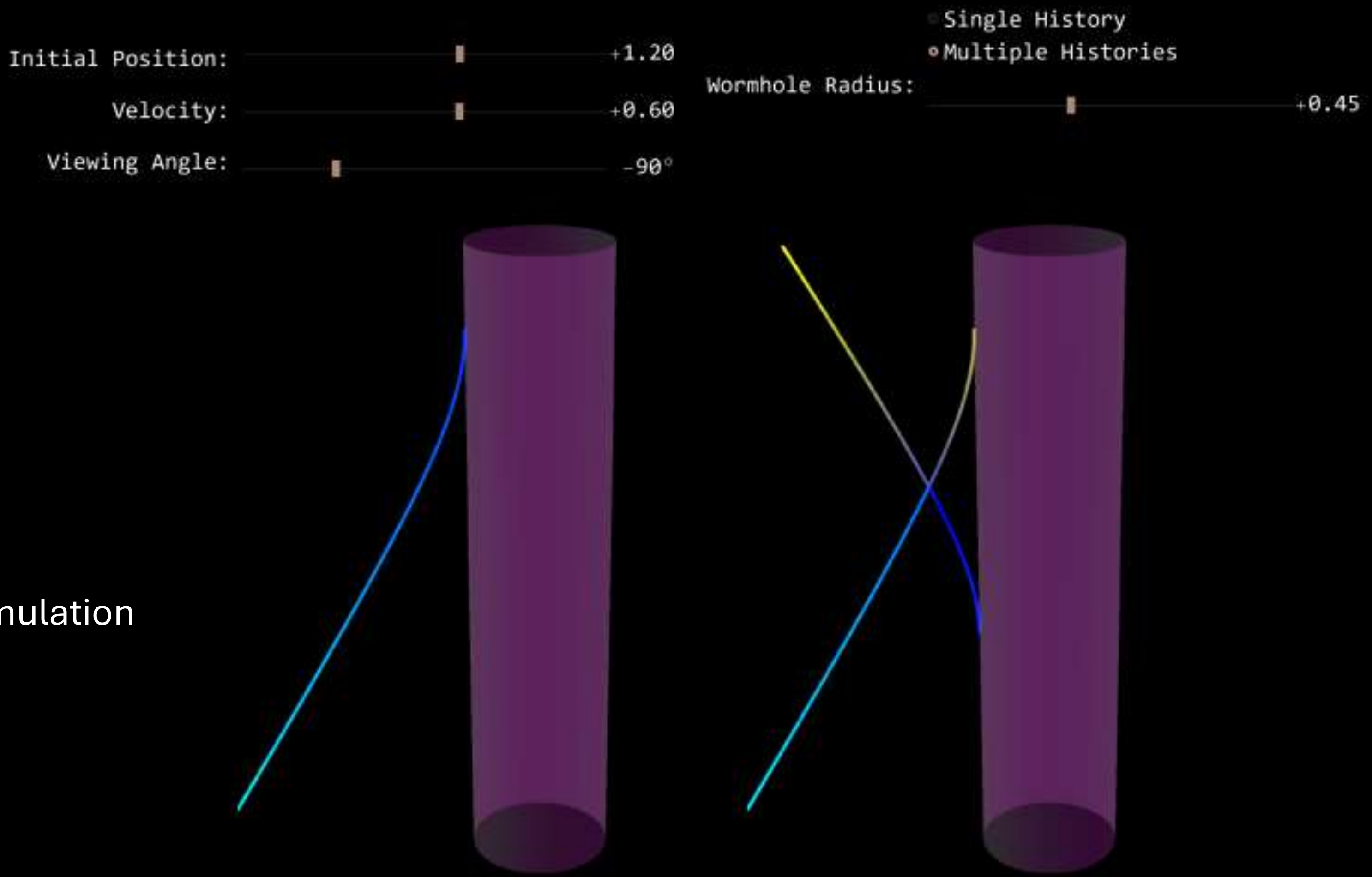
Springer





https://github.com/bshoshany/WormholeParadoxSimulation

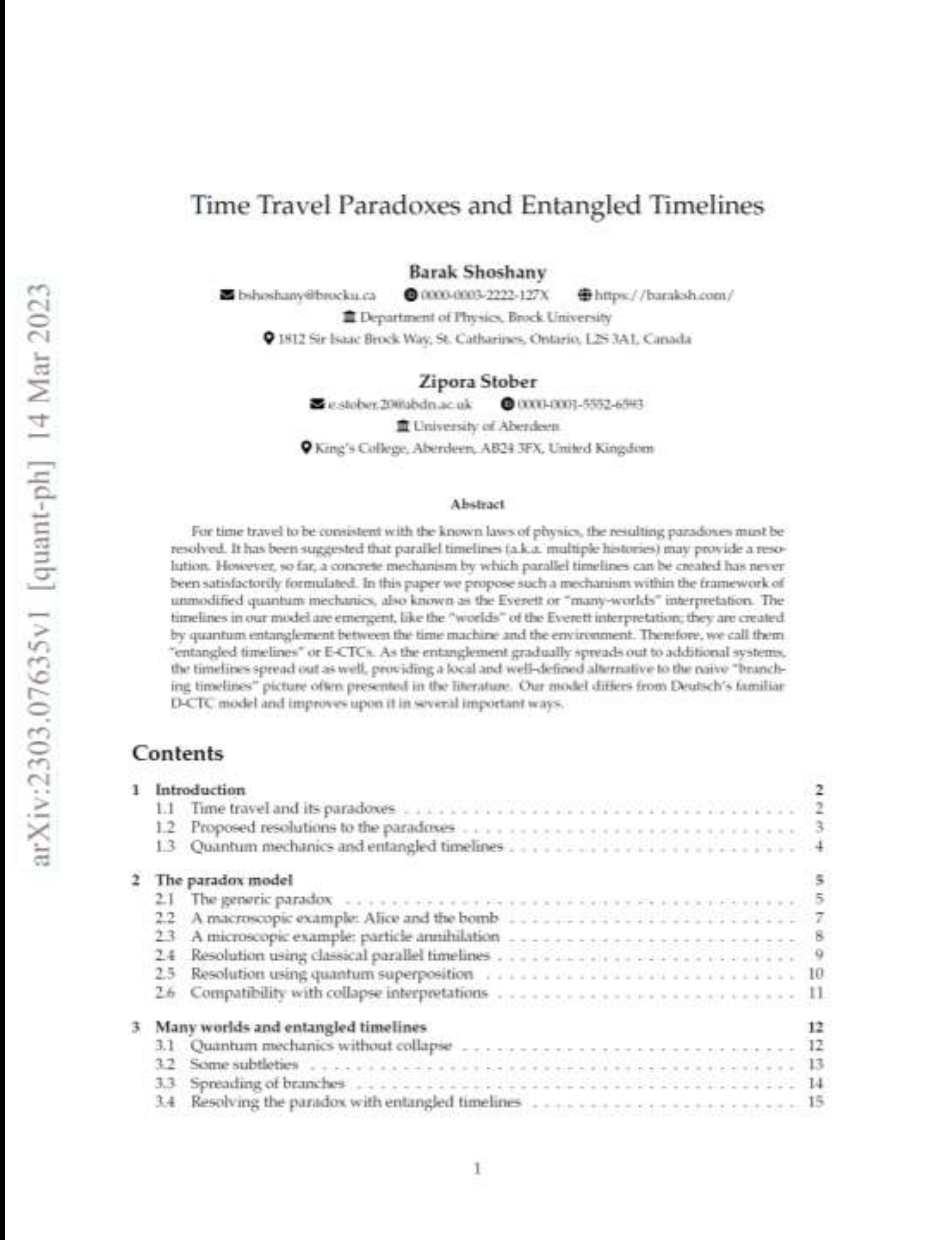
Time Travel Paradoxes and Entangled Timelines

With Zipora Stober

arXiv:2303.07635

Main results:

- First concrete model for resolving paradoxes with parallel timelines.
- Uses many-worlds interpretation.
- Resolves wide range of paradoxes.
- Timelines are emergent from entanglement.
- Propagate locally, gradually, and causally.



arXiv:2303.07635v1 [quant-ph] 14 Mar 2023

Time Travel Paradoxes and Entangled Timelines

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Abstract

For time travel to be consistent with the known laws of physics, the resulting paradoxes must be resolved. It has been suggested that parallel timelines (a.k.a. multiple histories) may provide a resolution. However, so far, a concrete mechanism by which parallel timelines can be created has never been satisfactorily formulated. In this paper we propose such a mechanism within the framework of unmodified quantum mechanics, also known as the Everett or "many-worlds" interpretation. The timelines in our model are emergent, like the "worlds" of the Everett interpretation; they are created by quantum entanglement between the time machine and the environment. Therefore, we call them "entangled timelines" or E-CTCs. As the entanglement gradually spreads out to additional systems, the timelines spread out as well, providing a local and well-defined alternative to the naive "branching timelines" picture often presented in the literature. Our model differs from Deutsch's familiar D-CTC model and improves upon it in several important ways.

Contents

1

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\|0\rangle \otimes \|1\rangle$	$\|1\rangle \otimes \|1\rangle$
🕑	**Nothing happens**	**Time travel is prevented**
$t = 1$	$\|0\rangle \otimes \|1\rangle$	$\|1\rangle \otimes \|0\rangle$
🌀	**Time travel occurs**	**Time travel does not occur**

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{alive}\rangle$	$\|\text{bomb}\rangle \otimes \|\text{alive}\rangle$
🕑	**Nothing happens**	**Bomb explodes, Alice dies**
$t = 1$	$\|\text{empty}\rangle \otimes \|\text{alive}\rangle$	$\|\text{bomb}\rangle \otimes \|\text{dead}\rangle$
🌀	**Alice sends a bomb back in time**	**Dead Alice cannot send a bomb**

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{not annihilated}\rangle$	$\|\text{particle}\rangle \otimes \|\text{not annihilated}\rangle$
🕑	**Nothing happens**	**Past and future particles annihilate**
$t = 1$	$\|\text{empty}\rangle \otimes \|\text{not annihilated}\rangle$	$\|\text{particle}\rangle \otimes \|\text{annihilated}\rangle$
🌀	**Particle goes into time machine**	**Particle doesn’t go into time machine**

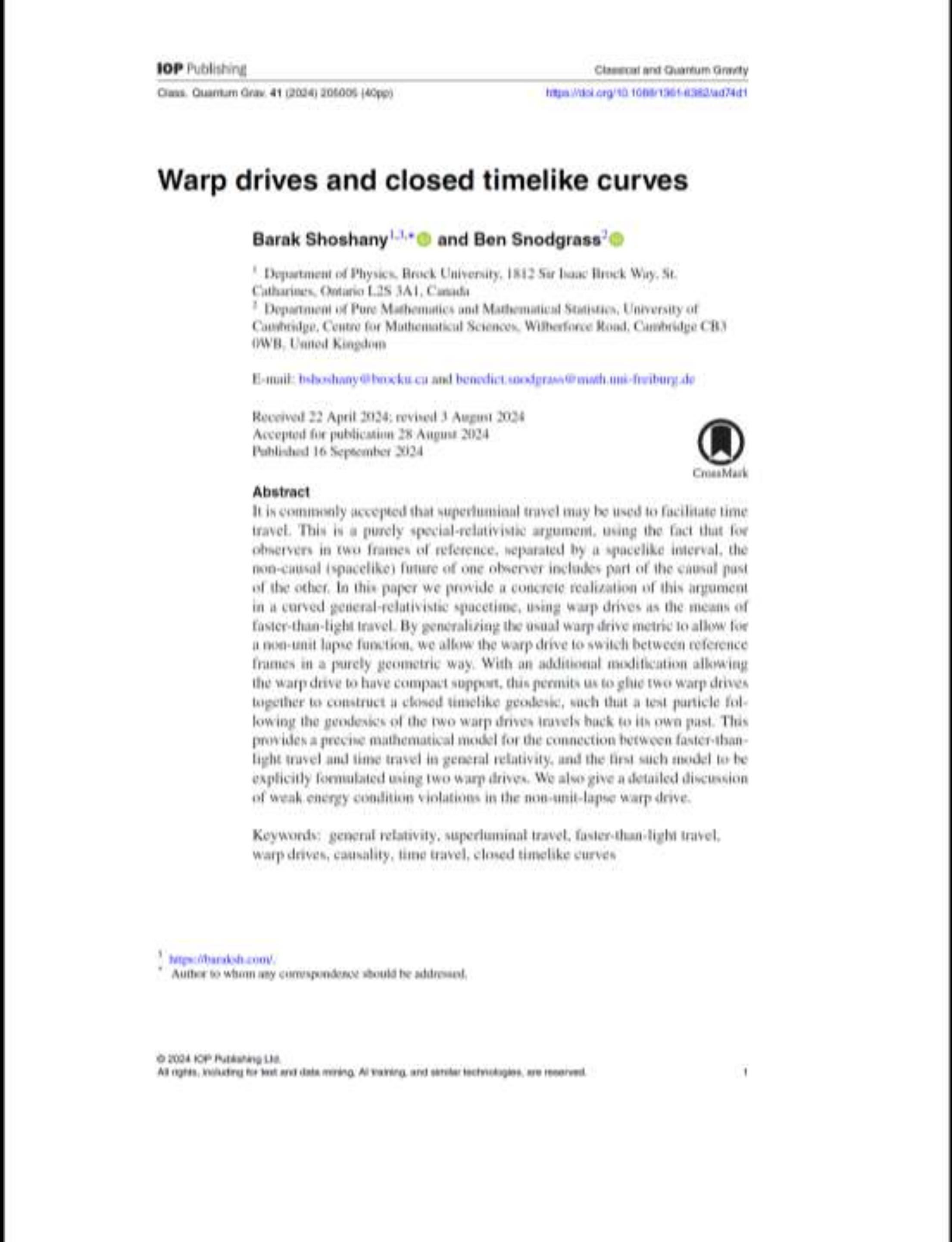
Warp Drives and Closed Timelike Curves

With Ben Snodgrass

Main results:

- Showed explicitly that warp drives can be used for time travel.
- “Glued” two warp drives together.
- Showed exotic matter is needed even for non-FTL warp drives.

Class. Quantum Grav. 41 205005 (2024)



IOP Publishing Classical and Quantum Gravity
Class. Quantum Grav. 41 (2024) 205005 (40pp) https://doi.org/10.1088/1361-6382/ad74d1

Warp drives and closed timelike curves

Barak Shoshany[1,3,*] and Ben Snodgrass[2]

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CrossMark

Abstract

It is commonly accepted that superluminal travel may be used to facilitate time travel. This is a purely special-relativistic argument, using the fact that for observers in two frames of reference, separated by a spacelike interval, the non-causal (spacelike) future of one observer includes part of the causal past of the other. In this paper we provide a concrete realization of this argument in a curved general-relativistic spacetime, using warp drives as the means of faster-than-light travel. By generalizing the usual warp drive metric to allow for a non-unit lapse function, we allow the warp drive to switch between reference frames in a purely geometric way. With an additional modification allowing the warp drive to have compact support, this permits us to glue two warp drives together to construct a closed timelike geodesic, such that a test particle following the geodesics of the two warp drives travels back to its own past. This provides a precise mathematical model for the connection between faster-than-light travel and time travel in general relativity, and the first such model to be explicitly formulated using two warp drives. We also give a detailed discussion of weak energy condition violations in the non-unit-lapse warp drive.

Keywords: general relativity, superluminal travel, faster-than-light travel, warp drives, causality, time travel, closed timelike curves

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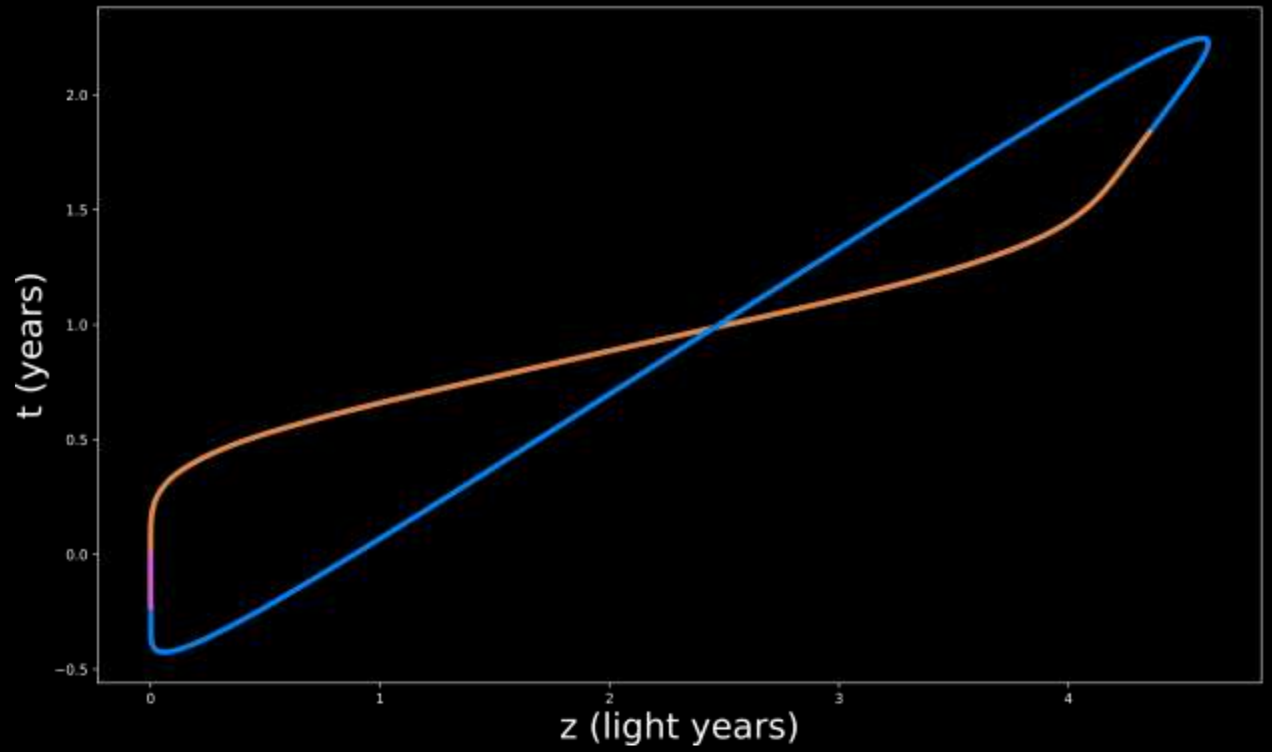
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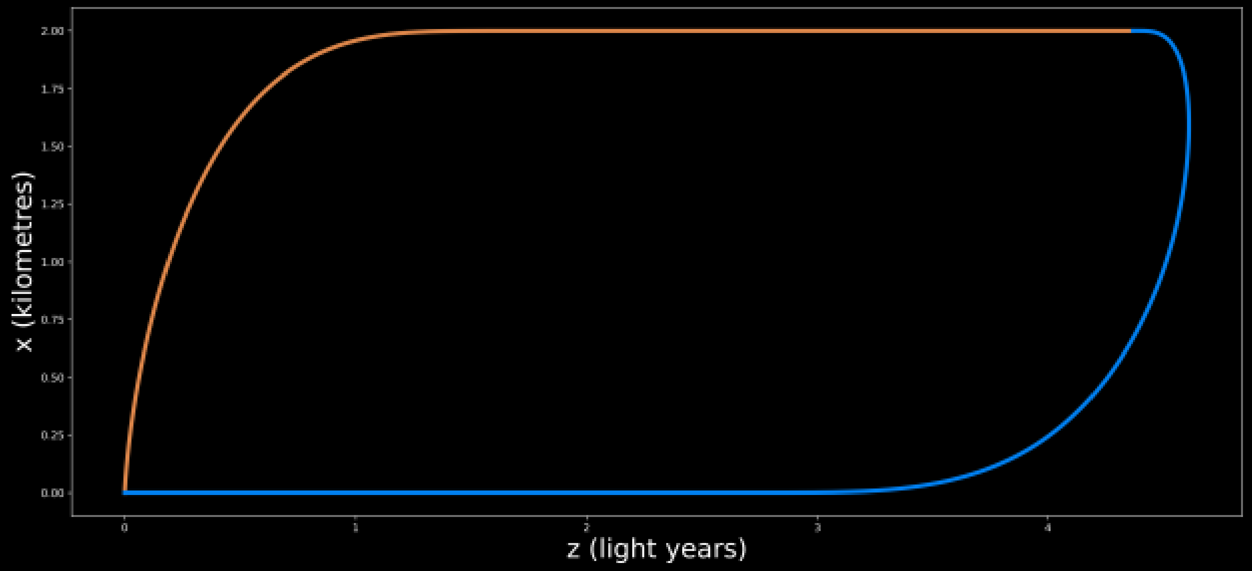
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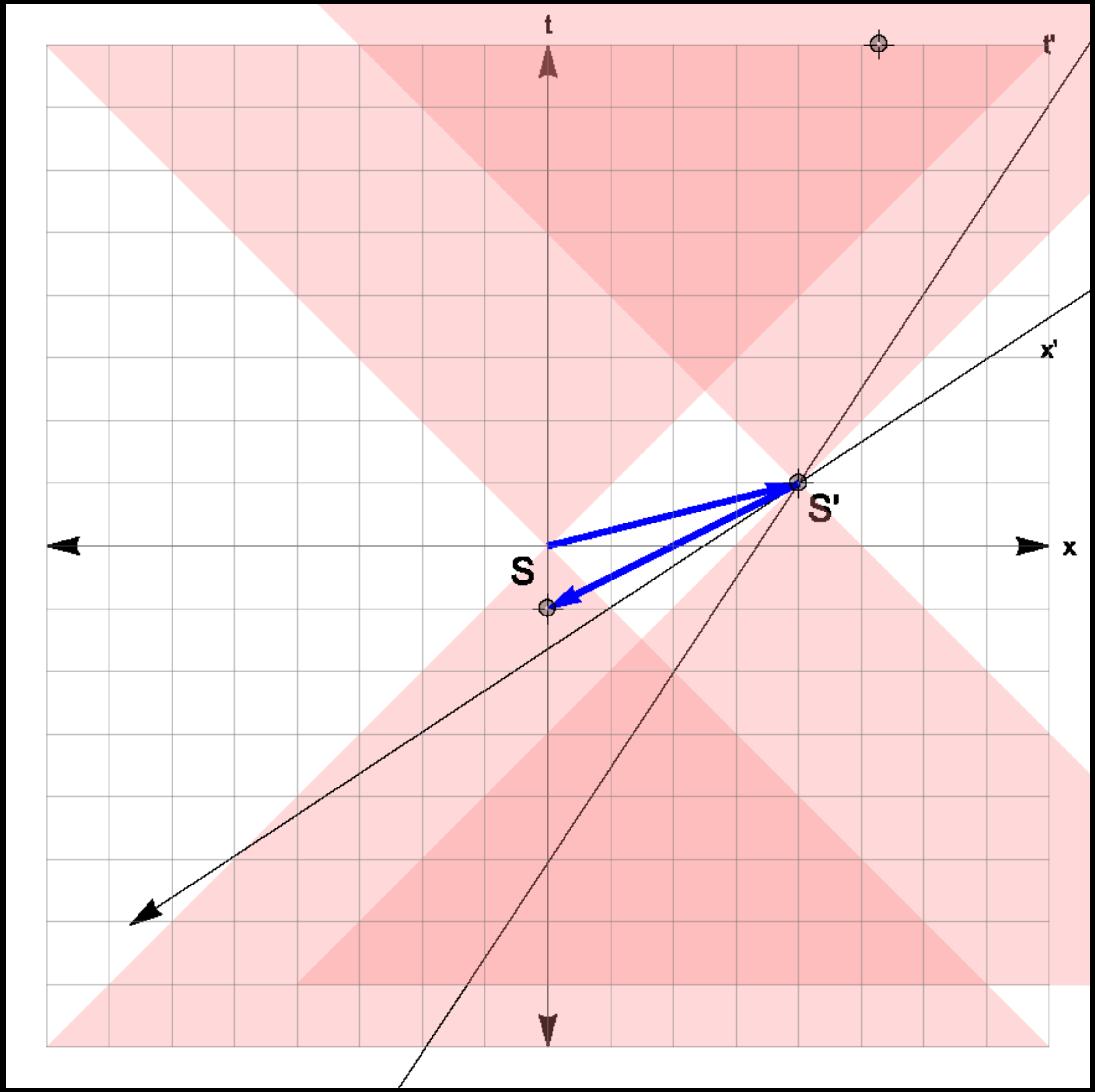
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Wormhole Nucleation via Topological Surgery in Lorentzian Geometry

With Alessandro Pisana

arXiv:2505.02210

<u>Main results:</u>

- Usually wormholes being studied are assumed to already exist.
- Trying to create a wormhole leads to singularities.
- We found a way to do it without singularities.

arXiv:2505.02210v1 [gr-qc] 4 May 2025

Wormhole Nucleation via Topological Surgery in Lorentzian Geometry

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We construct a model for the nucleation of a wormhole within a Lorentzian spacetime by employing techniques from topological surgery and Morse theory. In our framework, a 0-surgery process describes the neighborhood of the nucleation point inside a compact region of spacetime, yielding a singular Lorentzian cobordism that connects two spacelike regions with different topologies. To avoid the singularity at the critical point of the Morse function, we employ the Misner trick of taking a connected sum with a closed 4-manifold—namely $\mathbb{CP}^2$—to obtain an everywhere non-degenerate Lorentzian metric. This connected sum replaces the naked singularity—unavoidable in topology-changing spacetimes—with a region containing closed timelike curves. The obtained spacetime is, therefore, non-singular but violates all the standard energy conditions. Our construction thus shows that a wormhole can be "created" without singularities in classical general relativity.

I. INTRODUCTION

A. Motivation

The roots of the idea that non-linearities in Einstein field equations could give rise to topologically nontrivial configurations of spacetime trace back to Wheeler and Misner [1]. In an attempt to recover classical concepts such as *mass without mass* or *charge without charge*, they introduced the *geon*, an isolated gravitational-electromagnetic entity such that classical mass and unquantized electric charge can be recovered from its non-trivial topological features [2].

Among the simplest examples of geons are wormholes: handles attached to spacetime. These have been extensively investigated as theoretical solutions of Einstein field equations [3–5]. However, all known classical Lorentzian wormhole solutions are eternal, since their nucleation or annihilation is usually relegated to quantum gravity effects [6]. Our work seeks to push the boundaries of the classical theory and explore whether these topologically non-trivial configurations can arise from trivial ones in purely classical settings.

Important constraints on this investigation are imposed by two theorems due to Geroch [7]. The first theorem states that it is always possible to interpolate between two closed 3-manifolds via a Lorentzian cobordism. However, if the two 3-manifolds are non-homeomorphic, Geroch second theorem requires that the spacetime contains either singularities or closed timelike curves (CTCs).

Two fundamental perspectives emerge in addressing classical topology changes. The first prioritizes causality and leads to scenarios where the interpolating spacetimes include regions with metric degeneracies [8, 9], Morse singularities [10–12], or instantons [13–19]. The second emphasizes the equivalence principle and permits topology changes at the expense of causality [20, 21], leading to conceptual issues such as causality paradoxes [22–24].

In this work we adopt the latter perspective, maintaining an agnostic viewpoint on whatever chronology and energy conditions should be imposed on the spacetime—especially since CTCs may well be an inevitable byproduct of the wormholes themselves [25], as well as other forms of superluminal travel [26].

Specifically, we implement topological surgery techniques [27, 28] and results from Morse theory [29–31] for

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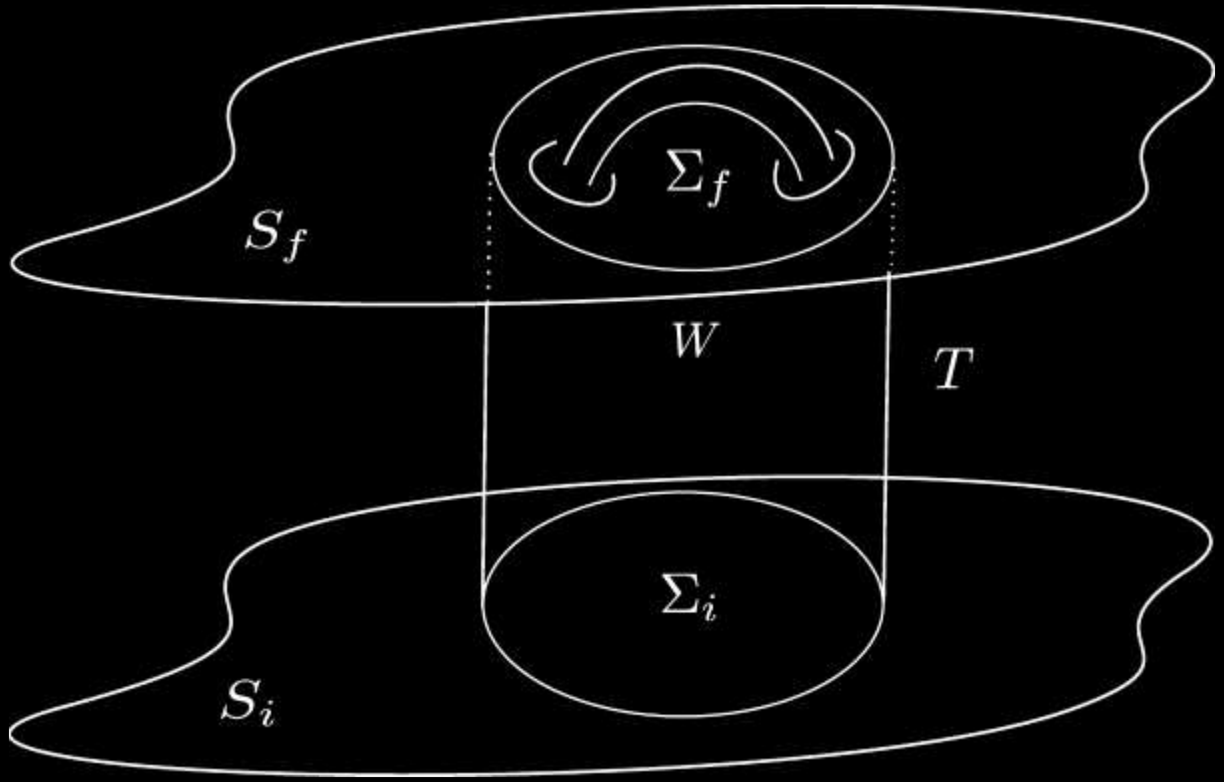
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S_f
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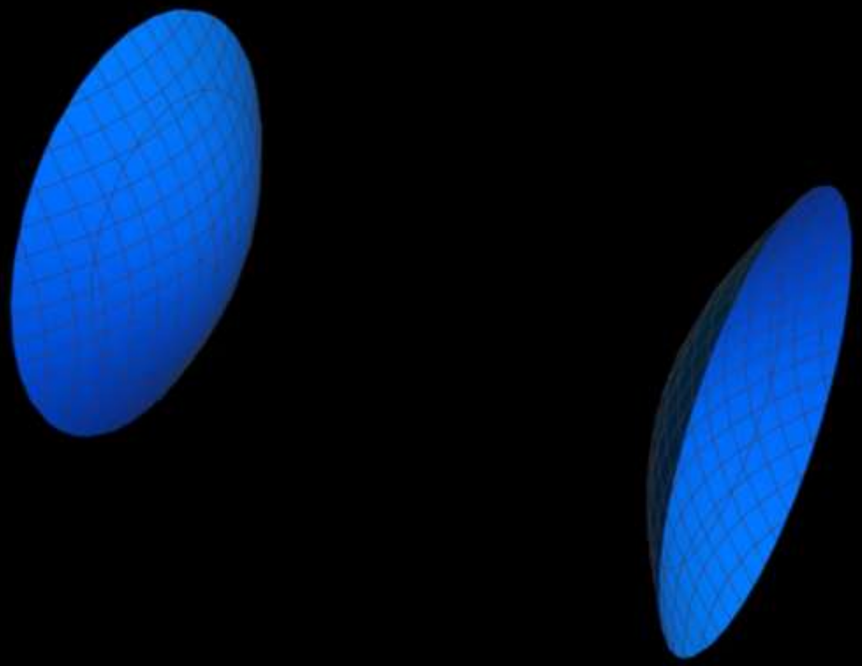
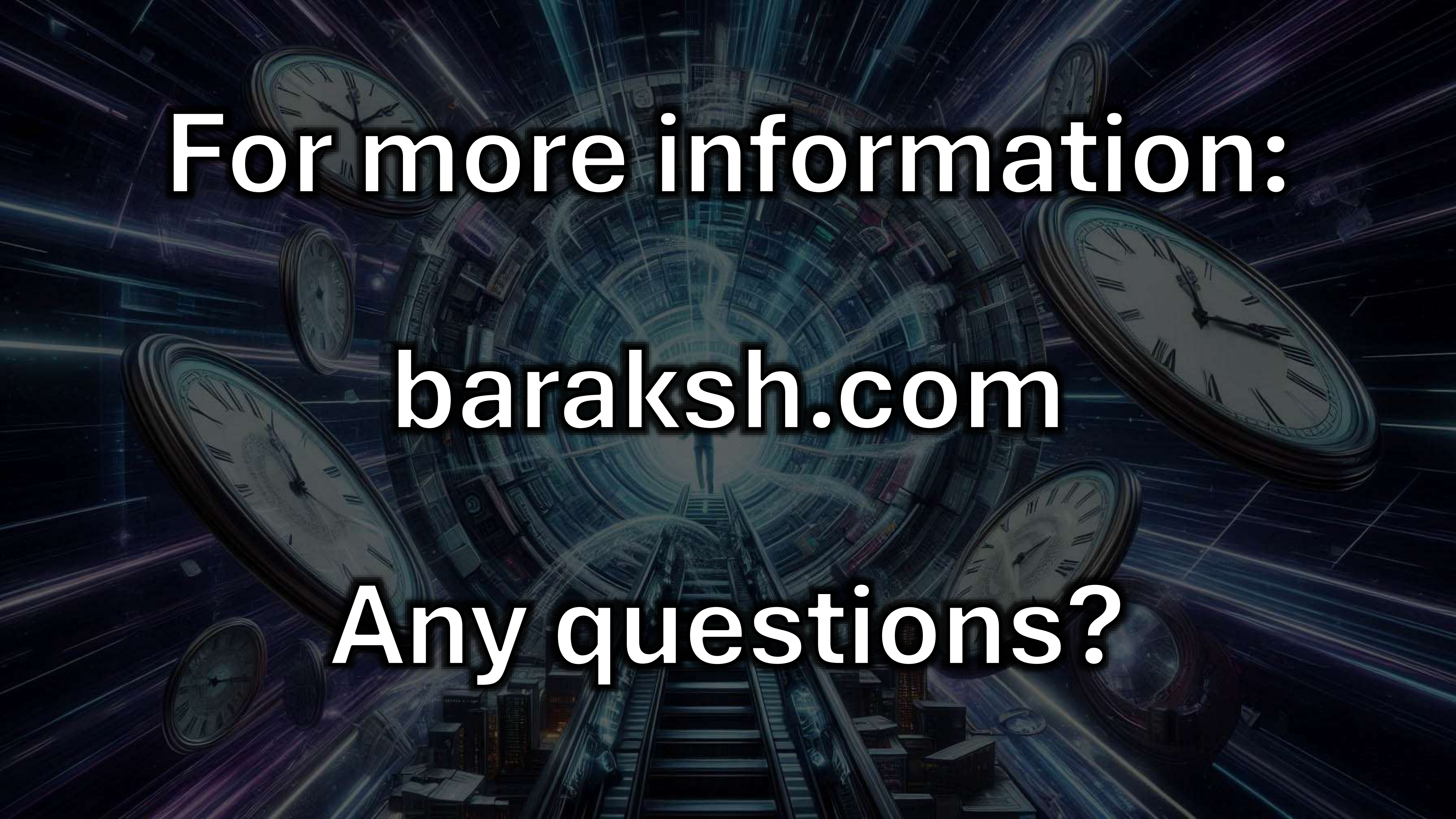
Σ_i
S_i




For more information:
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Any questions?